Top Quark Production and Decay at CDF II

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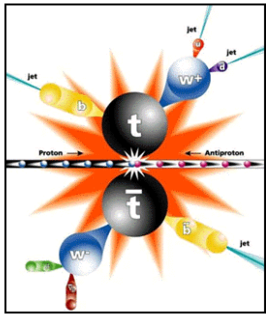
Introduction

In Run I the top quark was discovered and its properties studied with 109 pb^{-1} of data. It stands out among the fermions because of its large mass (M_{top} = 174 ± 5 GeV), which is on the order of the weak scale, and because it decays so quickly (Γ_{top} ~ 1.4 GeV) that it does not hadronize before decaying.

The predictions the Standard Model makes for the top quark in Run II are very specific:

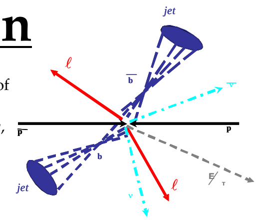
- σ_{tt} = 6.7 +0.7-0.9 pb (at $\sqrt{s}$ = 1.96 TeV) [1]
- decays to a W boson and a b quark over 99% of the time
- kinematic distributions



The CDF Run II detector is a major upgrade which allows more of the detector to be used, and used more effectively, than in Run I. With a dataset nearly twice the size of that in Run I, we have done a suite of measurements of the properties of the top quark to test the accuracy of these Standard Model predictions.

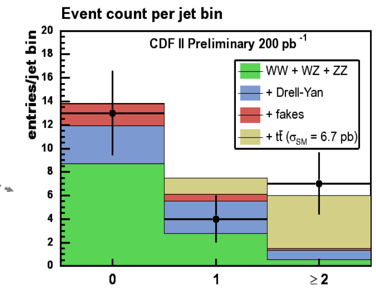
[1] R. Bonciani et al., Nucl. Phy. B 529 (1998) 424
as updated in hep-ph/0303085.

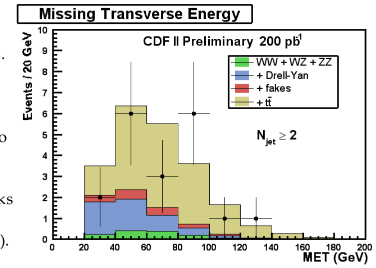
Dilepton

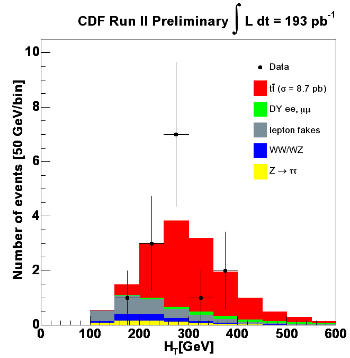


In the dilepton channel of $t\bar{t}$ decay, both Ws decay to a lepton-neutrino pair, creating two high-p_T leptons and a large missing transverse energy. Along with two or more jets (from the two b quarks and any initial- or final-state radiation), this is a distinctive if rare experimental signature with a small Standard Model background.

We measure the pair production cross-section in this channel using two complementary counting experiments. Both require two high-p_T leptons in the final state, along with two or more jets and significant missing transverse energy, but they use different criteria to identify the second of the two leptons. One ("lepton + track") seeks to maximise the acceptance by only requiring the second lepton candidate to be an isolated track, and the other ("identified leptons") is a Run I -style analysis which seeks to maximize sample purity by requiring the second candidate to be identified as a specific lepton type (e or μ).







Top: Total count of candidate events in the data satisfying the lepton + track selection criteria, compared to the Standard Model prediction, for events with 0, 1, and 2 or more jets.

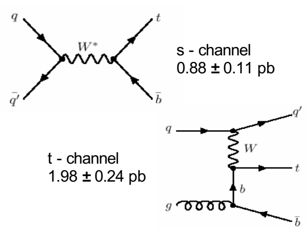
Above center: Total missing transverse energy of lepton + track candidate events, compared to the Standard Model expectation.

Left: Total scalar sum of transverse energy in candidate events where both leptons pass lepton ID requirements, compared to the Standard Model expectation. Large total transverse energy is a distinctive feature of top decay events.

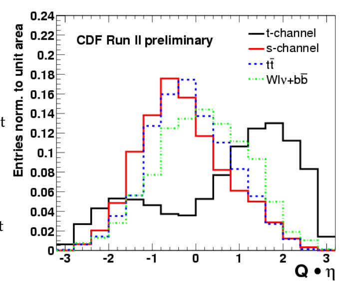
Lepton+Track (200 pb^{-1}):
σ_{tt} = $6.9^{+2.7}_{-2.4}$ (stat) ± 1.3 (syst) pb
Identified Leptons (193 pb^{-1}):
σ_{tt} = $8.7^{+3.9}_{-2.6}$ (stat) ± 1.5 (syst) pb

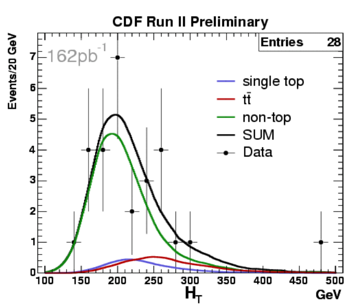
Single Top

The top quark has been observed in strongly-produced $t\bar{t}$ pairs, but single top production, a weak process, has yet to be seen. The single top cross-section measures the CKM matrix element V_{tb} directly, and an anomalous result could indicate new physics.



For both the s- and t- channels, candidate events have exactly one tight lepton (from the W from t→Wb) and two jets, one of which must be b-tagged. The total invariant mass of the final state must be consistent with M_t. Monte Carlo templates are fit to the data for two different kinematic distributions to determine the signal content of the candidates. The fitted signal content is consistent with zero, so we quote our result as a confidence limit.





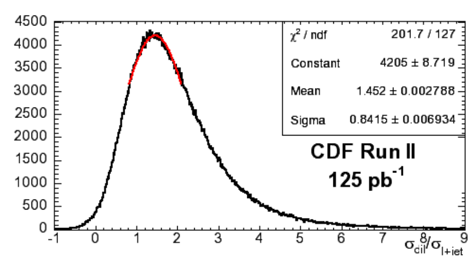
Top: **Diagrams** of Standard Model single top production in the s- and t-channels; predicted cross-sections

Above: Monte Carlo templates for expected **(lepton charge)** * **(untagged jet pseudorapidity)**.

Left: Monte Carlo templates for **total scalar sum of transverse energy in the event**, compared to the data.

162 pb^{-1}, 95% CL limits:
Combined: σ < 13.7 pb
t-channel: σ < 8.5 pb

Cross Section Ratio



Ideally, if all of the signal data events in the dilepton and lepton + jets cross-section measurements are Standard Model top, the ratio between the measured cross-sections should be 1. Significant deviation from that would be a catchall indicator of new physics – it could be caused by Br(t→Wb) ≠ 1, or by an unknown process being included in the signal sample for one of the measurements. Nearly all of the systematics are correlated among these measurements and cancel in the ratio, giving it a small systematic uncertainty, although it is still a statistics-limited measurement.

Left: Numerically constructed probability distribution function of the ratio of cross-sections that we observe in the data, given our measured cross-sections and their respective errors.

$R_\sigma = \sigma_{dilepton}/\sigma_{l+jet}$ (125 pb^{-1}):
95% CL limit: 0.46 < R_σ < 4.45
or R_σ = 1.45+0.83-0.55

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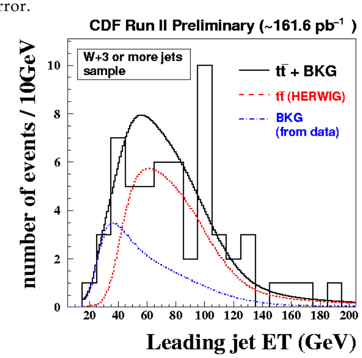
Lepton + Jets

While the lepton + jets channel has a relatively large cross-section times branching ratio, the 1 lepton + missing transverse energy + 3 or more jets signature has a significant Standard Model background from W+jets. Given the challenging S/B ratio of the lepton + jets sample, all of the lepton + jets cross-section measurements search for the basic signature above, and then apply different additional criteria and techniques to increase the signal purity.

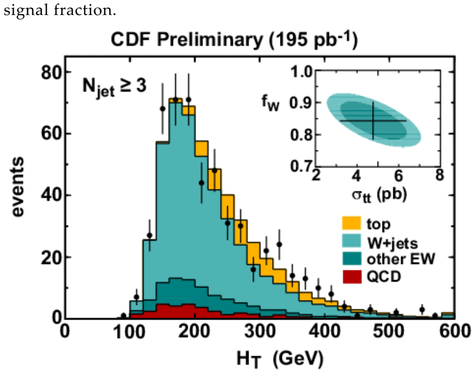
Kinematics, SVX b-tagging (162 pb^{-1}):
$\sigma_{tt} = 6.0^{+1.5}_{-1.8}$ (stat) ± 0.8 (syst) pb

Tagging b-jets via a displaced secondary vertex purifies the signal sample. Signal and background templates of the leading-jet E_T spectrum (good signal discriminant since jets from top are harder than those from W+jets) are fit to the data. Background templates are derived from non-tagged data instead of from Monte Carlo, reducing the systematic error.



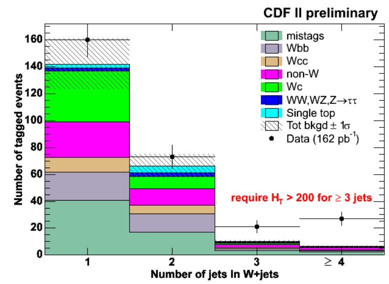
Kinematics, No b-tagging (195 pb^{-1}):
σ_{tt} = 4.7 ± 1.6 (stat) ± 1.8 (syst) pb

Top events have on average a higher total scalar sum of transverse energy (H_T) than their Standard Model backgrounds. Monte Carlo templates for the H_T of both signal and background are fit to the data to determine the signal fraction.



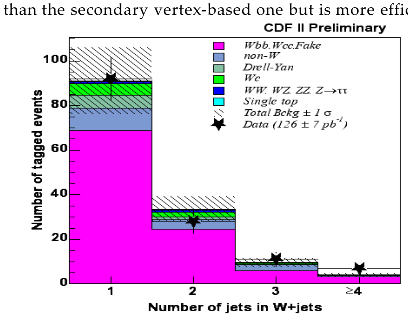
Counting, SVX b-tagging (162 pb^{-1}):
σ_{tt} = 5.6 ± 1.2 (stat) ± 0.7 (syst) pb

At least one jet is required to have a displaced vertex (SVX b-tag) to reduce the background. Using both data and Monte Carlo we predict the amount of Standard Model background in the tagged (signal) sample. The excess of events with 3 or more jets can be attributed to top.



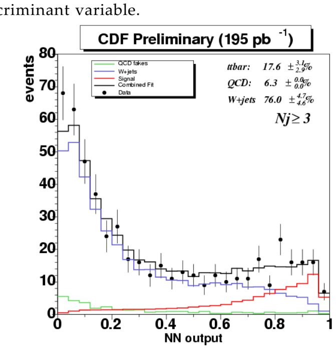
Counting, Soft Lepton b-tag (126 pb^{-1}):
$\sigma_{tt} = 4.1^{+4.0}_{-2.8}$ (stat) ± 1.9 (syst) pb

Muons from the semileptonic decay of a b quark can also tag b-jets. This tagging algorithm tags more background than the secondary vertex-based one but is more efficient.

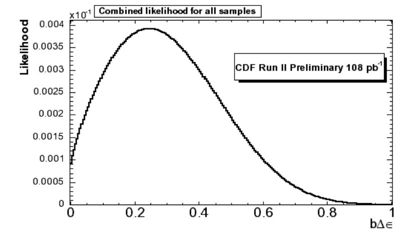


Neural Net Fitter, No b-tagging (195 pb^{-1})
σ_{tt} = 6.7 ± 1.1 (stat) ± 1.6 (syst) pb

Kinematic distributions for top events differ slightly from those for W+jets for a number of variables. A neural network incorporates all of this information into a single discriminant variable.



t → Wb Branching Ratio



The probability to tag a jet from a b quark in top events depends not only on the tagging efficiency but also on the branching ratio Br(t→Wb). Therefore the ratio of single- to double-tagged top lepton + jets events measures the product of the branching ratio and the efficiency, b·ε. From a likelihood fit, b·ε is $0.25^{+0.22}_{-0.18}$. The tagging efficiency is known from an independent source to be 0.45 ± .05, so the branching fraction can be derived from b·ε:

Branching Fraction (108 pb^{-1}):
$B(t \to Wb) = 0.54^{+0.49}_{-0.39}$

Summary

We have studied the production and decay of the top quark using in the Run II data, and found consistency among the measurements and with the Standard Model. However, these measurements are still statistics-limited, and new features may appear as we integrate more data and refine our analysis techniques. We hope to have systematics-limited top measurements in many channels in the near future given the continued excellent performance of the Tevatron.